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Healthier Choices: Oleogels as a Smart Fat Replacement Solution

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ABSTRACT

Fats and oils, mainly made of triglycerides, are crucial in food for flavor, texture, and structure. While dietary fats were once broadly linked to health risks, current research focuses concern on trans and saturated fats, prompting global efforts to limit their intake. This has driven the development of healthier alternatives, such as oleogels—semi-solid gels made by structuring liquid oils using agents like waxes, ethyl cellulose, and phytosterols. Oleogels offer fat-like qualities with better nutritional value and oxidative stability, making them ideal for replacing harmful fats in foods, especially processed meats.
Oleogels are created through mechanisms like crystalline networks, polymer systems, or molecular self-assembly and are produced using techniques such as direct dispersion, emulsion templating, or oil adsorption. Each method has specific advantages, including enhanced stability and reduced oxidation, though challenges remain in ensuring product consistency and consumer acceptance. The emulsion template method is particularly effective for structuring high-liquid-content oils. Oleogelation supports health, regulatory, and environmental goals by improving fatty acid profiles and reducing animal fat usage. This review highlights the promising role of oleogels in the food, pharmaceutical, and cosmetic industries, particularly as a sustainable and healthier fat substitute in processed meat products.
Key words: Oleogels, Structuring agents, Saturated fats, Trans fats, Food, Pharmaceutical, Cosmetic industries

INTRODUCTION

Fats and oils primarily consist of triglycerides, which contain a mix of monounsaturated, polyunsaturated, and saturated fatty acids, along with various minor components. Typically, food products contain a blend of these triglycerides. Although fats were once thought to negatively impact consumer health, leading to the widespread promotion of low-fat diets, recent research has indicated that only trans and saturated fats are linked to the development of cardiovascular diseases (Liu et al. 2017, Zhu et al. 2019). In food, saturated and trans fatty acids serve a technological purpose, contributing to characteristics like flavor, palatability, and texture (Pehlivanoglu et al. 2018). Additionally, triglycerides form a supracolloidal network that turns fats into solid or semi-solid substances, providing structure to food products (Marangoni et al.2012, Patel et al. 2015).

Interest in functional lipids and improving the nutritional quality of lipid-containing foods has grown significantly due to regulatory bans on artificial trans fats and recommendations to limit saturated fat intake in foods. The World Health Organization (WHO, 2019) advises that total fats, saturated fats, and trans fats should make up less than 30%, 10%, and 1% of total energy intake, respectively. Addressing the issue of trans fats, the U.S. Food and Drug Administration (FDA) declared in 2015 that partially hydrogenated oils, the primary source of artificial trans fats in processed foods, are not generally recognized as safe (GRAS).

Subsequently, WHO (2019) launched the "REPLACE" campaign to address industrially produced trans fats by reviewing their dietary sources, promoting healthier alternatives, adopting regulatory measures for elimination, monitoring trans-fat content in the food supply, understanding consumer preferences, raising awareness about the health impacts of fats, and ensuring policy compliance. Similarly, the European Food Safety Authority (EFSA) issued a report on June 8, 2018, highlighting the health risks of trans fats, noting a dose-dependent link between trans-fat intake and an increased risk of cardiovascular disease compared to other dietary fatty acids (EFSA 2018). Additionally, the European Commission (EU) introduced Regulation No. 649 on April 24, 2019, limiting industrial trans fats to 2 gram per 100 gram of total fat, excluding naturally occurring trans fats from animal sources.

As a result, food experts from both research and industry are tasked with finding ways to replace trans and saturated fats in foods without compromising their processing characteristics, technological functionality, or sensory appeal. These solutions must also align with consumer preferences, product demand, and regulatory requirements. Researchers have explored substituting trans and saturated fats with unsaturated fats from vegetable oils (Marangoni and Garti 2011). However, this approach introduces challenges, such as difficulties in handling and shaping, a greasier texture, reduced palatability, diminished flavor stability, and shorter shelf life due to lipid oxidation (Rousseau D 2007, Hasenhuettl and Hartel 2008). To create fats with solid-like properties and an improved fatty acid profile, structuring unsaturated oils became an essential area of focus (Mert and Demirkesen 2016).

Oleogelation is a process that creates a gel-like structure by incorporating liquid oil into a network formed by structuring agents, typically food-grade gelling materials such as waxes and polymers. This innovative technology has gained significant attention in the food industry due to its ability to transform liquid oils into semi-solid gels without requiring chemical additives or modifications. Oleogelation offers a healthier alternative to traditional fats in food products by reducing trans and saturated fats while maintaining desirable textural qualities (Manzoor et al. 2022).

What sets oleogels apart is their ability to retain the flow properties of liquid oils while replicating the texture of solid fats, making them highly versatile (Co and Marangoni 2012, Davidovich-pinhas M 2019, Silva et al. 2021). They have applications not only in the food industry but also in pharmaceuticals and cosmetics. In pharmaceuticals, oleogels are valuable for controlled drug release (Abdollahi et al. 2014, Montesano et al. 2020, Barroso et al. 2021), while in cosmetics, they are effective in delivering active ingredients and enhancing formulation (Puscas et al. 2020).

Meat processors face the challenge of developing low-fat meat products that are both nutritionally beneficial and sensorially acceptable to consumers. Replacing saturated fatty acids (SFA) with liquid oils enhances the fatty acid profile of meat products by increasing the levels of monounsaturated (MUFA) and polyunsaturated fatty acids (PUFA) and improving the n-6/n-3 and PUFA/MUFA ratios (Alvarez et al. 2012, Pintado et al. 2016, de Souza Paglarini et al. 2020). However, the high degree of unsaturation in liquid oils makes them prone to oxidation, which is a significant concern (Manzoor et al. 2022).

In contrast, oleogels offer greater oxidative stability than bulk oils. This stability arises from the entrapment of oil within the gel structure, which significantly inhibits oxidation (Hwang et al. 2018). A study by Ferrer-Gonzalez et al. (2019) demonstrated that meat batters prepared with soybean oil-cellulose-based oleogels exhibited higher oxidative stability compared to control meat batters containing lard or pork back fat.

The development of such innovative meat products requires careful optimization to ensure that they can be effectively marketed and accepted by consumers. Identifying commercially viable approaches, such as reformulation (Jimenez-Colmenero 2007, Barbut 2017, Serdaroglu et al. 2022), the use of fat replacers (Badar et al. 2021, Choi & Kim 2021, Serdaroglu et al. 2022) fat mimetics (Yilmaz and Daglioglu 2003, Youssef and Barbut 2011, Badar et al. 2021), or their combinations, is essential to reducing the fat content of meat products (Badar et al. 2021). In the subsequent write-up, this review focuses on the scientific basis and mechanisms of oleogelation, recent advances in the formulation and application of oleogels in meat products, current limitations, regulatory perspectives, and consumer acceptance regarding the use of oleogels in food systems.

OLEOGELS AND OLEOGELATORS

Gels are three-dimensional structures capable of immobilizing a liquid phase. They consist of two main components: a liquid solvent phase (either polar or non-polar) and a gelling agent that forms the three-dimensional network. Based on the polarity of the immobilized liquid, gels are categorized as either hydrogels (with a polar solvent like water) or organogels (with an organic solvent) (Sagiri et al. 2014). When the organic phase consists of edible oil, organogels are referred to as oleogels. These can be described as an organic liquid trapped within a thermo-reversible, anhydrous, viscoelastic material through a three-dimensional gel network. Oleogels transform liquid oil into a gel-like structure with viscoelastic properties (Rogers et al.

2009, Stortz et al. 2012).
Interestingly, many gels require only small amounts of organogelators to form, making them comparable to bulk fat materials since they predominantly consist of edible liquid oil, often exceeding 97% by weight (Patel et al. 2014).
Organogels can be classified into physical or chemical gels based on the type of chemical interactions involved in the gelation process (Sagiri et al. 2014). Oleogelators are generally divided into two categories: self-assembly systems and crystal particle systems (Fig. 01). In self-assembly systems, the oleogelator organizes at the molecular level within the oil phase, while in crystal particle systems, crystals form through nucleation and subsequent growth within the oil (Co and Marangoni 2012; Dassanayake et al. 2011).

Another classification distinguishes between polymeric and low-molecular-weight organogelators. Low-molecular-weight organogelators include triacylglycerols, diacylglycerols, monoacylglycerols, fatty acids, fatty alcohols, waxes, wax esters, and sorbitan monostearate. Phytosterol-based organogelators are particularly interesting because, in addition to their excellent structuring properties, they may help reduce blood cholesterol (Huang et al. 2010, Patel and Dewettinck 2015) and have been used in margarine formulations (Duffy et al. 2009). Polymeric organogelators, many of which are food-grade and cost-effective, hold the greatest potential for food applications. Among these, ethyl cellulose stands out as a particularly promising option (Co and Marangoni 2012, Stortz et al. 2012, Zetzl et al. 2012).

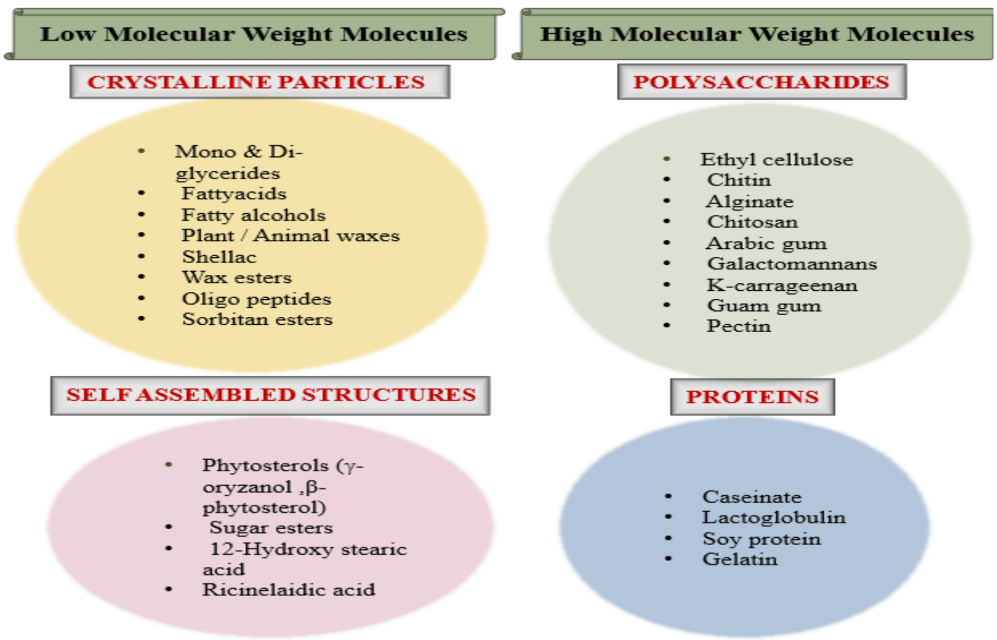

Fig 01. Classification of oleogelators

Table 01: Summary of common oleogelators and their applications

Type of Oleogelator	Examples	Source	Key Characteristics	Applications	References
Waxes	Beeswax, Candelilla wax, Rice bran wax, Carnauba wax	Natural (plant/animal)	High oil binding capacity, solid at room temp, good oxidative stability	Sausages, bakery fats, spreads	Marangoni & Garti (2011); Davidovich-Pinhas (2019); Silva et al. (2021)
Fatty Acid Derivatives	Stearic acid, Cetyl alcohol, Glycerol monostearate	Plant-based or synthetic	Good structuring, moderate melting points	Margarines, processed meat emulsions	Patel et al. (2015); Mert & Demirkesen (2016)
Sterols and Stanols	β-sitosterol, γ-oryzanol, Cholesterol	Plant (e.g., rice bran), animal	Transparent gels, potent oil structuring, bioactive potential	Functional foods, drug delivery	Co & Marangoni (2012); Barroso et al. (2021)
Polysaccharides	Ethyl cellulose, HPMC, Alginate	Plant-derived	Thermally stable, suitable for hot processing	Meat patties, pharmaceutical carriers	Abdollahi et al. (2014); Montesano et al. (2020)

Proteins (Emerging)	Soy protein isolate, Whey protein isolate	Plant/ dairy	Under development, biofunctionality	Edible delivery systems, emulsions	Patel et al. (2015); Manzoor et al. (2022)
Composite Systems	Sterol–polysaccharide, Wax–polymer blends	Multi-origin	Tunable texture, enhanced oxidative protection	Designer meat fats, spreads	Hwang et al. (2018); Serdaroglu et al. (2022)

TYPES OF OLEOGELS

Currently, various gelators like waxes, glyceryl monostearate, hydroxypropyl methyl cellulose (HPMC), and ethyl cellulose (EC) are commonly used to prepare oleogels. Depending on the quantity of the gelling agent, these oleogels are categorized into mono component or multi-component types. Oleogels can also be classified based on their formation mechanism, including crystalline particle network oleogels, polymer network Oleogels, self-assembled crystalline systems, and indirect templated system Oleogels (Xu et al. 2022) which are being detailed below.

Oleogels of crystalline particle network

Small molecule gelators create a three-dimensional network of crystalline particles, with the crystallization of the gelator substance being the main factor behind the formation of networks in crystalline particle-based oleogels. As the crystalline particles form clusters, they trap the liquid oil within the network, which solidifies into a tight crystalline structure upon cooling. Common small molecule gelators that follow the particle crystallization principle include monoglycerides, diglycerides, fatty acids, fatty alcohols, biowaxes, and wax esters.

One of the most widely used oleogels is formed using wax as the structural agent, where the wax self-assembles into a continuous crystal lattice, trapping the liquid oil and forming an oleogel. Blake et al. (2014) found that adding wax to the oleogel made the crystal chain structure more intricate, leading to the formation of multiple crystal regions. Wax lipids, particularly saturated wax ester acids with carbon chains ranging from 10 to 31, form oleogels similar to those made from fatty acids in edible oils (such as sunflower oil), essential oils (like lavender oil), and hydrocarbons (like diesel oil). As the carbon chain length increases, the minimum concentration required for gel formation in liquid oils and fats decreases. At lower concentrations, wax esters form crystal flakes or needles in edible oils, unlike saturated glycerides (Daniel and Rajasekharan, 2003). Additionally, Rogers et al. (2008) studied the crystallization of 12-hydroxystearic acid in vegetable oils, investigating the stability of its self-assembled crystal structure through non-isothermal nucleation and crystallization.

Phytosterols, as well as mixtures of phytosterols and β-sitosterol, are frequently used as gelling agents. Among these, β-sitosterol, estradiol, and dihydrocholesterol are the most common choices. Bot et al. (2011) observed that fibrils formed during the gelling process of oleo-hydrogels. Unlike pure oleogels, the self-assembled tubules of phytoretinol are mainly monohydric sterol crystals that create fibrous structures in emulsions.

Oleogels of the polymer network

The key requirement for creating polymer oleogels is the cross-linking or non-covalent self-assembly of polymeric components through chemical bonding (Xu et al. 2022). Ethyl cellulose (EC) is the only known polymeric gelling agent that can be directly dispersed in oil and can be modified in various ways to suit different applications. As a semi-crystalline polymer derivative, EC undergoes a sol-gel transition in the presence of liquid oil, facilitated by physical forces. The hydrophobic and semi-crystalline nature of the molten mixture is maintained below the sol-gel transition temperature. Physical forces, such as van der Waals forces and hydrogen bonds, help form a stable, uniform three-dimensional network structure, trapping the hydrophobic oil phase. Zhang et al. (2019) studied the structure of cinnamon oil oleogels formed by cross-linking EC molecules at high temperatures. As the viscosity of EC increased, the oleogel structure became denser, improving the oil's binding capacity and stability. Kai Zhang's team also explored EC at three different viscosities for cinnamon essential oil (CEO) oleogels, examining their physicochemical properties and emulsion stability (Zhang et al. 2019). Their findings showed that as EC viscosity increased, the network structure of the CEO-EC oleogels became tighter, confirming the earlier observations (Zhang et al. 2019). This behavior, in which EC undergoes a sol-gel conversion in the presence of liquid oil, relies on the polymers' ability to bond through physical interactions. EC was combined with monoglycerides (MG) and candlestick wax (CW) oleogels to enhance the rheological properties of EC by increasing its solubility and forming hydrogen bonds between EC's hydroxyl groups and MG (Rodríguez-Hernández et al. 2021). EC can alter the functional characteristics of oleogels by interacting with polar functional groups in the oil phase, making it useful for food ingredients or the oral administration of fat-soluble compounds. When heated to the phase transition temperature, EC melts and disperses into the liquid oil, and upon cooling, it cross-links within the hydrophobic phase, forming a gel structure (Patel and Dewettinck 2016, Zhou et al. 2017, Zhang et al. 2019).

Oleogels of the self-assembly systems network

Supersaturation occurs when the organogelator-solvent mixture's melting point is lower than the organogelator itself, causing the gelator molecules to self-assemble through a nucleation process. Self-assembling gelling agents, such as 12-hydroxystearic acid and ceramides, regulate the flow of liquid oil by forming spiral or twisted crystalline fibers. These agents mimic the natural self-assembly and crystallization abilities of triacylglycerols, controlling the hierarchical assembly of gelling agents via weak molecular interactions like hydrogen bonding, van der Waals forces, electrostatic interactions, dipole forces, and hydrophobic forces (Van Esch and Feringa 2000). Bot and Agterof (2006) explored how the molecular structure of oil-forming agents affects gelation, using dihydrocholesterol, cholesterol, β-sitosterol, and dulcitol from sunflower oil to self-assemble into firm, transparent gels with γ-sitosterol. The gelation ability is primarily influenced by hydrogen bonding between the hydroxyl group of sitosterol and the carbonyl group of oryzanol, and it is also affected by the degree of desaturation in the cholesterol ring structure (Bot et al. 2009, van Duynhoven et al. 2010, Patel et al. 2013).

Oleogels of indirect templated system

Direct oleogel preparation methods have limitations due to the high temperatures required, which can lead to oil oxidation and mass loss. To address this, researchers have explored indirect template-based approaches for oleo gel formation (Martins et al. 2017, Meng et al. 2018, Wang et al. 2020) . These include emulsion template methods (Erinç and Okur, 2021), foam template methods (Oh et al. 2019), and solvent exchange methods (Davidovich-Pinhas et al. 2016).

In the emulsion template method, an emulsion with high oil content is used as a framework to produce oleo gels. This involves forming an emulsion where interactions between emulsifier polymers within the droplets create a network structure. After specific treatments, the continuous phase comprises solid fat crystals, while the aqueous phase remains within the gel network. The final step involves drying to remove water, yielding the oleo gel.

However, the indirect method has drawbacks. The preparation process often introduces additional components, such as proteins, and the drying step is necessary to eliminate the aqueous phase. This dehydration process can destabilize the interface, leading to oil phase aggregation and oxidation of unsaturated oils, which negatively impacts the construction and stability of the oleo gel system.

Table 02: Oleo gel formation strategy and findings recorded

Oleogelator	Liquid phase	Method	Findings	Reference
Monocomponent				
Beeswax	Grapeseed oil	Crystalline particle	Rise in the proportion of wax from 5 to 15% leads to increased enthalpy of crystallization and melting point	Yi et al. (2017)
Carnauba wax	Canola oil	Crystalline particle	Greater enthalpy is required for carnauba wax-based oleo gels	Yi et al. (2017)
Beeswax	Canola oil	Crystalline particle	Better cohesive and adhesive properties are exhibited with beeswax oleogels	Lim et al. (2017)
Candelilla wax	Canola oil	Crystalline particle	High hardness and low peroxide values were noticed with candelilla wax oleogels	Lim et al. (2017)
Monoglyceride	High oleic sunflower oil	Crystalline particle	Formation of oleogel and its properties were affected by cooling temperature profiles	Palla et al. (2019)
Monoglycerides	High oleic sunflower oil	Crystalline particle	Physical properties of Oleogels were significantly improved with the application of High intensity ultrasound	Giacomozzi et al. (2020)
Ethyl cellulose	Canola oil and Soyabean oil	Polymeric network	Solvent polarity affects the mechanical behaviour of the ethyl cellulose oleogels	Gravelle et al. (2016)
Sorbitan monostearate	Mustard oil	Self-assembly	Interaction among the hydroxyl groups of sorbitan monostearate governs the gel network	Sagiri et al. (2016)

12-hydroxy stearic acid	Sunflower oil	Self-assembly	12-hydroxy stearic acid dimer have the strongest interaction during the self-assembly process	Jiang et al. (2020)
Hydroxypropyl methyl cellulose	Soyabean oil	Emulsion-templated	Better structure of oleogel was due to the presence of intramolecular and intermolecular hydrogen bonding	Meng et al. (2018)
		Multicomponent		
Monoglycerides and phytosterols	Sunflower oil	Crystalline particle	Mixed crystal system was formed by multicomponent oleogel	Bin Sintang et al. (2017)
Monoglycerides and phytosterols	Sunflower oil	Crystalline particle	The synergistic interaction creates a robust gel network	Kouzounis et al. (2017)
Ethyl cellulose, stearyl alcohol and stearic acid	Canola oil	Crystalline particle	With certain combination of oleogelators, the flow behaviour of gels altered.	Gravelle et al. (2017)
Adipic acid and carnauba wax	Soyabean oil	Crystalline particle	Gel strength and crystallinity were improved by adipic acid	Aliaslkhiabani et al. (2020)
Monopalmitate and carnauba wax	Soyabean oil	Crystalline particle	Synergistic interaction was noticed in the process of gelation	Yang et al. (2020)
γ-oryzanol and β-sitosterol	Flaxseed oil and sunflower oil	Self-assembly	Promising features such as low opacity and tailored mechanical strength were noticed in the produced oleogels	Martins et al. (2019)

METHODS OF PREPARATION OF OLEOGELS

Oleo gels can be constructed using three primary methods: direct dispersion, indirect methods, and oil adsorption.

Direct dispersion method is commonly used for solid fats and builds upon traditional techniques for dispersing waxes, fatty acids, monoglycerides, and ethyl cellulose (EC). In this process, the gelling agent is dissolved in liquid oil by heating it above its melting point. The mixture is then cooled, either naturally or through controlled shearing at specific temperatures. During cooling, nucleation and crystallization occur, leading to polymerization and the formation of self-assembled structures. Zhao et al. (2020) found that oleogels made from a single gelling agent often struggle to replicate the characteristics of traditional solid fats. However, combining different oleogel agents can enhance the network structure, resulting in oleogels with improved properties (Fig 02)

Table 03. Gelation conditions and application of oleogels in food

Oleogelator	Oil	Gelation conditions	Application	Reference
Carnauba wax (CW)/adipic acid(AA) mixture 50:10, 40:20, 30:30, 20:40, 10:50 (*w/w*)	Soyabean oil (SO)	CW/AA (6%) were dissolved in SO at 150°C until complete dissolution and cooled down at ambient temperature (1 °C/min).	fat replacement in cake and beef burger	Aliasl Khiabani, et al. (2020)
Beeswax (BW) 8%	Linseed oil (LO)	8% (*w/w*) BW was dispersed under stirring in heated LO (80°C) for 30min and cooled at room temp	Fat substitution in frankfurters	Franco et al. (2019)
Candelilla wax (CW) 3 and 6%	Canola oil (CO)	Heating to 150°C, under gentle agitation for 15 min and cooling at room temperature.	Partial replacement of shortening in cookies	Mert et al. (2016)

Sunflower and Carnauba waxes (SW, CW) 3, 7 and 10%	Hazelnut oil (HO)	Heating to 90°C, stirring vigorously for 5 min and cooling at ambient temperature	Comparative study with a commercial shortening	Ogutcu et al. (2014)
Carnauba wax	Olive oil & Flaxseed oil	Heating to 90°C, stirring vigorously at 400 rpm and cooling at ambient temperature and refrigerated at 3°C	Comparative study with commercial shortening in meat biscuits	Sonia et al. (2024)

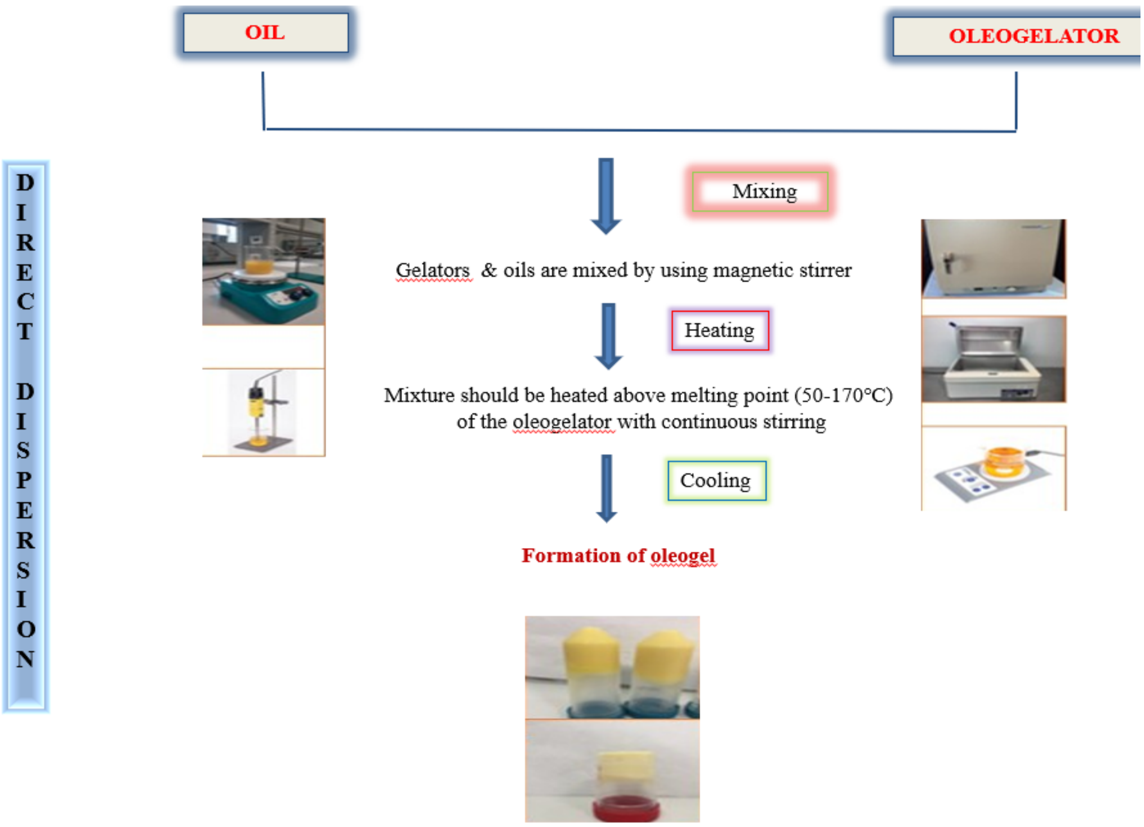

Fig 02. Direct dispersion method

The indirect method involves incorporating a polymer into an aqueous solvent or emulsion to structure vegetable oil into an emulsion gel (Fig 03). The water is then removed through freeze-drying or heat-drying, preserving the gel's tight grid structure. This structure effectively traps large amounts of liquid oil, preventing leakage even during extended storage. This method has garnered attention for its ability to produce oleogels with varied properties and structures by selecting colloidal particles with specific characteristics and modifying the emulsion template. Patel et al. (2014a) demonstrated this approach by using gelatin and xanthan gum as emulsifiers in an oil-to-water ratio of 6:4, creating emulsion templates that were oven- or freeze-dried to produce oleogels with high oil content. Another gelation technique, the oil adsorption method, involves creating porous structures in the aqueous phase or increasing fluid density near the interface to form an oleogel. Tanti et al. (2016) found this method could replace hydrogenated oils as stabilizers for peanut butter and partially or fully substitute oil in cookie frostings. Patel et al. (2015) further explored gel fats and oleogels made from water-soluble food polymers using emulsion and foam template methods. They discovered that combinations like methylcellulose (MC) and xanthan gum or gelatin and xanthan gum could transform liquid vegetable oils into high-strength, thixotropic soft solids with liquid oil content exceeding 97%. This eco-friendly technique avoids chemical modifications or cross-linking agents, offering potential as a sustainable alternative to traditional margarines and shortenings in baking. Despite its promise, this method faces challenges in managing oil oxidation during drying and dehydration. Additionally, the mechanism by which cross-linked networks stabilize liquid oils within biomolecular chains remains unclear. The adsorption process involves enriching material near the interface or increasing fluid density. Porous additives and absorbent fillers with high surface areas are often used to bind excess water, improving the consistency, flow, and texture of products. Patel et al.

(2015) also modelled the use of porous cryogels made from hydroxypropyl methylcellulose as aqueous foam templates. These cryogels, with high porosity, could absorb oil at over 100 times their weight. Shearing the oil-soaked material produced an oleogel containing 98% liquid oil. This novel, environmentally friendly method employs water foaming, freeze-drying, and shearing without relying on high temperatures, additives, or harsh chemicals.

Table 04. Application of oleogels in food

Oleogelator	Oil	Gelation conditions	Application	Reference
Pork skin (PS)	High oleic sunflower oil (HOSO)	PS, cooked for 40 min at 80 °*C* and comminuted in a blender, water and HOSO were mixed in the ratio of 1.5:1.5:1	Replacement of 50% pork backfat in bologna sausages	da Silva et al. (2019)
Canola protein isolate (CPI)	Canola oil (CO)	50% CO in water emulsion stabilized by high-pressure homogenization with 4% CPI was heated at 90°C for 30 min and dried at a 0.4 atm vacuum and 60 °C, followed by shearing	Replacing 50% of traditional shortening in the cake batter	Tang and Gosh (2021)
Gelatin (G) (3%, 5%) Xanthan gum (XG) (0.1%, 0.2%)	Canola oil (CO)	G and XG were dissolved in water, aerated by homogenization (13,000 rpm, 5 min), frozen at −20 °C overnight, and freeze-dried(24 h).Cryogel samples were saturated with CO and sheared by homogenization (0.5–2 min, 10,000 rpm).	Study about the ability of G and XG to produce oleogel through foam- templated method	Abdollahi et al. (2019)
HPMC	Canola oil	Foam template method	In meat patties	Oh et al. (2019)

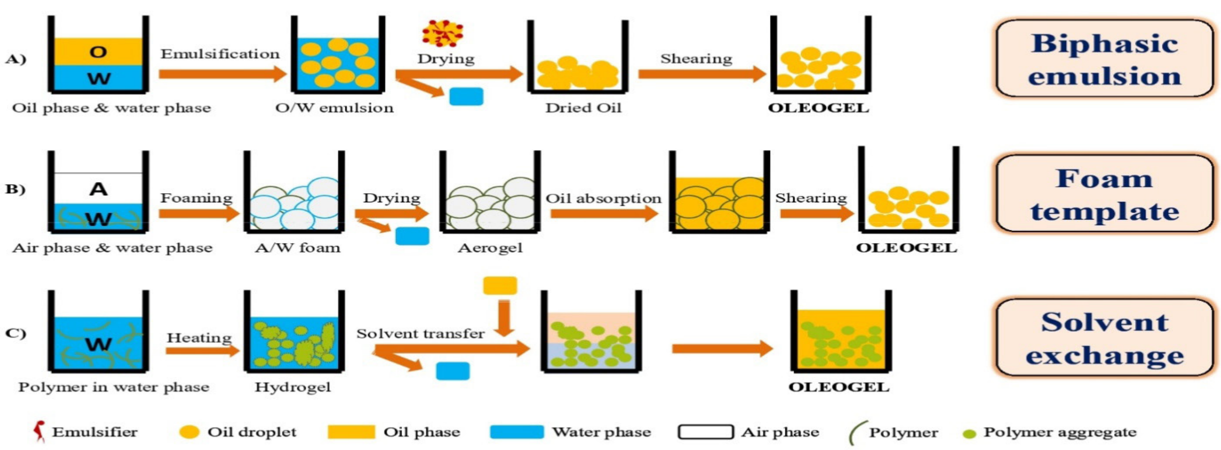

Fig 03. Indirect Dispersion methods

Oleogels generally demonstrate solid-like viscoelastic characteristics, with a higher storage modulus (G') than loss modulus (G"), indicating a well-organized internal structure. This makes them effective substitutes for solid fats in products like spreads, baked items, and processed meats. The properties of the oleogel—such as gel strength, elasticity, and flow—are largely influenced by the type and concentration of the oleogelator used, as well as the oil component. Waxes like beeswax and candelilla wax create firm, strong gels, while oleogels based on ethyl cellulose display shear-thinning behavior, which is advantageous for applications like emulsions and meat batters (Patel and Dewettinck, 2015).

Oleogels show a thermo-reversible gelation process—melting upon heating and reforming upon cooling. Differential scanning calorimetry (DSC) shows that the melting temperature is determined by the specific oleogelator used—waxes melt between 50–70°C, whereas ethyl cellulose gels melt at higher temperatures (140–160°C). This thermal behavior plays a crucial role in determining their functionality in thermally processed foods such as baked or fried products (Toro-Vazquez et al., 2007).

The microstructure of oleogels, examined via polarized light microscopy (PLM), scanning electron microscopy (SEM), or confocal microscopy, reveals crystalline networks or polymer fibrils that immobilize the oil phase. Wax-based oleogels display needle-like or platelet crystalline structures, while ethyl cellulose and protein-based oleogels form entangled polymeric networks (Co and Marangoni 2012).

Oleogels provide oxidative and physical stability to food products by trapping oil and reducing exposure to air and pro-oxidants. In emulsified or processed meat products, they help in maintaining product texture, minimizing liquid separation, and improving shelf-life. The stability depends on oil polarity, gelator type, and processing conditions (Meng et al. 2018).

OLEOGELS IN MEAT INDUSTRY

In the meat industry, oleogels have garnered interest due to their potential to replace or reduce animal fats in processed meat products like burgers, pates, sausages, while maintaining desirable sensory and functional properties (Ferdaus et al. 2024). The extensive experimental findings from scientists developing meat products with oleogels could serve as a foundation for the meat industry to adopt this alternative formulation, considering both nutritional and technological aspects. Fats play a crucial role in the structure and flavour of meat products, with their composition affecting binding properties, stability, and texture (Puscas et al. 2020). Replacing solid fats with oils rich in monounsaturated (MUFA) and polyunsaturated fatty acids (PUFA) offers a promising approach to creating healthier processed meat products, potentially lowering the risk of various diseases (Lenighan et al. 2019, Rabadán et al. 2021). In this context, the use of plant-based oleogels to develop antioxidant-rich processed meats with an improved fatty acid profile can be explored (Pintado and Cofrades 2020).

Key Roles of Oleogels in the Meat Industry

1. Fat replacement

   Oleogels are used to mimic the texture and functionality of solid fats in processed meat products such as sausages, patties, and canned meats by replacing animal fats with oleogels, products can achieve healthier lipid profiles with reduced saturated fats and increased unsaturated fatty acids (Silva et al. 2021, Bharti and Pathak 2022, Sonia et al. 2024).

2. Improving Nutritional Profile: Incorporating oleogels with high levels of unsaturated fats, such as those derived from olive oil, sunflower oil, or fish oil, enhances the nutritional value of meat products (Sonia et al.2024). This approach aligns with the growing consumer demand for healthier food options.

3. Maintaining Product Quality:
   - Texture: Oleogels help maintain the desirable mouthfeel and juiciness of meat products by replicating the properties of solid fats (Tavernier et al. 2017, Silva et al. 2021, Bharti and Pathak 2022).
   - Stability: Oleogels can improve the oxidative stability of meat products, especially when enriched with antioxidants (Ferrer-Gonzalez et al. 2019, Ozturk and Serdaroglu 2021, Silva et al. 2021, Sonia et al.2024).
   - Appearance: They contribute to the visual appeal of products by simulating marbling or other fat-based structures (Patel 2015, Tavernier et al. 2017, Silva et al. 2021).

4. Functional Benefits:
   - Fat binding: Oleogels enhance water and fat binding, reducing cooking losses (Martins et al. 2018, Ozturk and Serdaroglu 2021, Silva et al. 2021, Bharti and Pathak 2022).
   - Flavor Carrier: They act as effective carriers for fat-soluble flavors and bioactive compounds, ensuring a rich taste profile (Rogers 2009, Co and Marangoni 2012, Davidovich-Pinhas and Barbut 2015, Martins et al. 2018, Sonia et al.2024).

Applications in the Meat Industry

Sausages and Frankfurters:

Sausages are made from a mixture of ground meat and other non-meat ingredients, which improve their quality, taste, and flavor. Traditional sausages, rich in animal fat, are known for their enhanced flavor and succulence (Zampouni et al.2022). Among various types, cooked and smoked sausages, often referred to as frankfurters, wieners, or hot dogs, are the most popular. Traditional sausages typically contain about 27% fat and 10% saturated fatty acids (USDA, 2016). This highlights the importance of fat replacement in these high-fat products. However, replacing saturated fats with unsaturated fats poses challenges, such as maintaining consistency, preventing undesirable softness, and minimizing oxidative deterioration (Pintado and Cofrades, 2020).

Partial replacement of animal fat in sausages with oleogels has been shown to improve nutritional value without compromising structural integrity (Shilpa A, 2021). Research indicates that oleogels enhance the technical, functional, and sensory properties of sausages (Zetzl et al. 2014, Ozturk and Serdaroglu 2021, Bharti and Pathak 2022). Chicken-based bologna reformulated with rice bran wax-high oleic acid soybean oil (HOSO) oleogels showed improved stability, texture, and sensory attributes compared to controls, although pork fat provided more intense colour (Tarte et al.2020). Similarly, substituting pork back fat with HOSO-based oleogels improved emulsion stability and reduced cooking loss, with no negative effect on oxidative stability (Lima et al.2018).

Other studies, such as one involving the Spanish sausage fuet, in which pork back fat was replaced with beeswax oleogels or emulsion gels using olive and chia oils (Pintado et al. 2018). This reformulation resulted in a healthier fatty acid profile (lower SFA and n-6/n-3 ratio) without affecting oxidative stability or microbial properties. However, Fuets made with emulsion gels retained similar hardness to controls, while those with oleogels were softer and had lower sensory acceptance (Pintado and Cofrades, 2020).

Sensory acceptance is a key factor in commercializing reformulated products. Sausages with 20–40% pork back fat replaced by linseed oil oleogels were less preferred than the control (Franco et al.2019). However, replacing 50% pork back fat with olive oil oleogels improved texture, color, and nutritional profile, reducing saturated fats by 17.8% (Zampouni et al.2022). Sweet sausages reformulated with rice bran wax and rice bran oil oleogel showed enhanced softness, reduced saturated fat and cholesterol, and higher overall acceptance at 50% replacement (Issara, 2022).

The concentration of the gelator significantly affected product quality. Frankfurters made with 10% rice bran wax (RBW) oleogel experienced higher lipid oxidation but reduced cured flavor compared to those with lower RBW concentrations (Wolfer et al.2018). Oleogels also effectively controlled residual nitrite levels, enhancing safety by reducing carcinogenic risks, while improving fatty acid profiles (Pé et al.2020).

In conclusion, oleogels showed great potential as animal fat substitutes in sausages, offering healthier options with reduced saturated fat and improved safety while maintaining organoleptic properties, meeting consumer demand for healthier meat products.

Meat burgers and Patties:

Burgers and patties are highly regarded among various meat products due to their convenience as ready-to-eat and fast-food items, ease of preparation at home, widespread popularity, and adaptability for improving nutritional value. Typically, they consist of about 70–75% semi-frozen meat and 20–25% animal fat. However, given their high-fat content, reducing fat levels in these products is essential for promoting consumer health.

To address this, several studies have explored methods to enhance their nutritional quality (Afshari et al.2017; Guedes-Oliveira et al.2016). One recent study investigated reformulated pork patties made with two different amounts of linseed oil oleogels, using equimolar concentrations of γ-oryzanol and β-sitosterol as gelators (Koba et al. 2022). When compared to commercial hamburgers, patties containing 25% oleogel were found to have similar texture and cost-effectiveness. Sensory panelists rated these patties as the second most preferred option after the control hamburger (Martins et al.2019).

Another study examined the effects of replacing bovine back fat with oleo gels derived from pork skin and olive oil on the oxidative stability, physicochemical, technical, nutritional, and sensory properties of burgers (Lopes et al.2021). The reformulated burgers showed a 15% increase in protein content, an 80% reduction in fat, and an improved fatty acid profile. Although differences in appearance, color, and perceived fat were noted between raw and cooked burgers, the overall acceptability remained high, matching the control after cooking at 180°C. Additionally, the oleogel-based products demonstrated oxidative stability during seven days of storage at 4ºC.

The impact of oleogels on the quality attributes of vacuum-packaged reduced-fat beef burgers during storage was evaluated. Findings revealed that beef burgers made with olive oil oleo gel exhibited a nutritionally improved fatty acid profile, showing a 44% reduction in saturated fatty acids (SFA) and a 65% increase in unsaturated fatty acids (UFA). These burgers also demonstrated lower oxidation levels (as indicated by lower TBARS values), reduced hardness, chewiness, and springiness, along with higher cooking yields and greater overall acceptability (Özer and Çelegen, 2021).

An optimized oleo gel system, developed using carnauba wax (CW) and adipic acid (AA), was also studied (Aliasl et al.2020). The concentrations of the gelators were optimized at 2% CW and 4% AA, resulting in oleogels with desirable gel strength, improved oil-binding capacity, and enhanced thermal behavior and crystallinity. Using this oleogel complex, a reformulated beef burger was prepared replacing 50% of the animal fat. The resulting burger exhibited increased hardness and chewiness while maintaining acceptable color and sensory qualities (Aliasl et al.2020).

Similar observations were made in beef burgers prepared with oleogels based on ethyl cellulose and adipic acid at the same concentrations (Adili et al.2020).

Meat Batters:

Structured oils have been shown to alter the fatty acid composition of meat batters, particularly by increasing polyunsaturated fatty acids (PUFA) and decreasing saturated fatty acids (SFA). In a study by Totosaus (2019), pumpkin seed paste or ethylcellulose-based soybean oil oleogels were used to fully replace pork back fat in meat batters. The results indicated that oleogel-based batters had higher PUFA levels, reduced lipid oxidation, and lower calorie content due to the reduced fat content compared to the control. Specifically, SFA was reduced from 11.8% to 2%, PUFA increased from 0.3% to 5%, and the omega-6 to omega-3 ratio improved from 16.2 to 2. These oleogels did not alter the color and texture, and they exhibited lower oxidation values compared to the control sample containing beef fat. Furthermore, batters made with oleogels showed improved emulsion stability compared to those prepared with hydrogel emulsions. Hydrogel-based batters experienced clumping of fat globules and fat losses during cooking, which led to a reduction in fat content (Alejandre et al.2019).

Oleogels prepared from various oils, including sunflower seed, peanut, corn, and flaxseed oils, combined with different concentrations of ethyl cellulose (8%, 10%, and 12%), were tested as substitutes for pork fat to study their effect on the gel characteristics of pork batter. Oleogel-based cooked batters exhibited improved emulsion stability, increased hardness, gumminess, and chewiness, shorter relaxation times, and larger peak areas, indicating a higher content of immobilized water. As the ethyl cellulose concentration increased, hardness also increased, though cohesiveness and springiness remained unchanged. Batters made with pork back fat had larger fat globules and a lower L^* value compared to those made with organogels, although there was no significant difference in redness (a^* values) between the two (Shao et al.2020). Microstructural observations of the pork batters revealed that fat globules in the pork fat-based batter were much larger than those in the organogel-based batter. The smaller fat globules in the oleogel batter were suspended within the meat protein matrix, forming a uniform, continuous network that enhanced water retention and bound more soluble substances, leading to less cooking loss.

Significant differences in consumer acceptance and textural parameters were observed between the oleogel-based batter and the control (Pintado et al. 2015, Ferrer-Gonzalez 2019, Ozturk and Serdaroglu 2021). However, the pumpkin seed paste-based samples were preferred by consumers, despite color differences (Totosaus, 2019). A comparative study on replacing beef fat with hydrogels (containing 1.5% or 3% kappa carrageenan) and ethylcellulose oleogels (with 0%, 1.5%, or 3% glycerol monostearate) using canola oil in emulsion-type meat batters concluded that the reformulated products contained healthier lipids (Alejandre et al.2019).

Table 05. Application of oleogels in meat products

Product	Oleogel		% Replacement	Implications	References
	Oil	Gelator			
Beef burger	Sesame oil	10% Beeswax	25%, 50% - fat from beef flank and shank	Higher unsaturated fatty acids, lower acid and peroxide values	Moghtadaei et al.2018
Beef burger	Soyabean oil	Carnauba wax (CW) and adipic acid	8% beef fat	Better texture, colour and organoleptic properties	Aliasl et al.2020
Beef burger	Soyabean oil	Ethyl cellulose & Adipic acid	50% by fat from beef flank and shank	Acceptable colour and organoleptic characteristic	Adili et al.2020
Low fat pork burgers	44.39% olive oil, 37.87% linseed oil, 17.74% fish oil	11% ethyl cellulose, 11% beeswax, 3.67% sorbitan monostearate and curcumin 0.2%	0.6% pork back fat	Increased omega-3 fatty acids content, Improved Sensory characteristics	Gomez estaca et al.2020

Beef burger	Sesame oil	Ethyl cellulose	50-100% of animal fat	Reduced cooking loss, fat absorpyion and oxidation process	Moghtadaei and Soltanizadeh 2021
Low fat beef burgers	Olive oil	1% sodium alginate, 1% carrageenan and 15 glycerol monostearate	5-15% beef fat	65% increase of unsaturated fatty acids, 44% decrease of saturated fat and 51% reduction of total fat	Issue 2020
Pork patties	Linseed oil	γ-oryzanol and β-sitosterol	25 and 75% pork fat	Higher sensory acceptance for 25% substitution	Martins 2019
Meat patties	Canola oil	HPMC	Beef fat	Improved oxidative stability during storage	Oh et al.2019
Meat biscuits	Olive oil and flaxseed oil	Carnauba wax	100% of commercial shortening	Superior fatty acid composition and sensory evaluation scores	Sonia et al.2024
Meat batters	Soyabean oil	Ethyl cellulose+ cellulose+ avicel	Pork back fat	Increased PUFA content in soyabean based oleogels	Totosaus, 2019
Batter	Canola oil	Ethyl cellulose and glycerol monostearate	Beef fat	Saturated fatty acids decrease from 11.8% to 2%	Alejandre et al., 2019
Pork batter	Sunflower, peanut, corn and flaxseed oils	Ethyl cellulose – 8%, 10.5% and 12%	Pork fat	Higher hardness, gumminess & chewiness	Shao et al.2020

Consumer acceptability of oleogel-incorporated processed meat products

Numerous studies have indicated that meat products partially substituted with oleogels (typically 30–50% replacement) are generally well accepted by consumer panels, with overall liking scores comparable to those of traditional high-fat counterparts (Serdaroglu et al. 2017, Sen and Kayaardi 2019, Barbut and Boles 2021). However, complete replacement of animal fats can sometimes negatively affect sensory attributes such as texture and juiciness, potentially reducing consumer acceptance (Serdaroglu and Nacak 2018, Barbut and Boles 2021). To address these challenges, the use of optimized oleogel formulations—such as blends incorporating beeswax, sunflower oil, and natural antioxidants—has demonstrated encouraging results in preserving sensory quality (Yilmaz and Ogutcu 2015, Sen and Kayaardi 2019, Feyzi et al. 2021). Notably, health-conscious consumers show a marked preference for oleogel-enriched meat products, appreciating their improved lipid profiles and clean-label characteristics (Martins et al. 2018, Espert et al. 2020, Dominguez et al. 2021).

Regulatory status of oleogels and oleogelators

United States (FDA) – In the U.S., many components commonly used in oleogel formulations—such as beeswax, sunflower oil, and ethyl cellulose—are classified as Generally Recognized as Safe (GRAS) for food use. However, the use of novel combinations or emerging structuring agents in oleogels may require submission of a GRAS notification or a food additive petition for regulatory clearance. While there are currently no specific regulations addressing "oleogels" as a distinct category, each constituent ingredient must comply with existing food safety regulations.

European Union (EFSA) - Within the EU, oleogel components must align with Regulation (EC) No 1333/2008 concerning food additives. When oleogels incorporate novel structuring systems or ingredients not previously used in food, they may be classified under the Novel Food Regulation (EU) 2015/2283. The European Food Safety Authority (EFSA) requires comprehensive toxicological, nutritional, and compositional evaluations as part of the approval process for such novel food applications.

India (FSSAI) - The Food Safety and Standards Authority of India (FSSAI) has not yet issued specific regulations for the use of oleogels in meat or other food products. Nevertheless, individual ingredients commonly used in oleogels, such as beeswax (INS 901) and sunflower oil, are already approved under the Food Safety and Standards (Food Product Standards and Food Additives) Regulations, 2011. Introduction of new structuring agents or oleogel systems may necessitate prior approval as a novel food or additive, based on safety and regulatory evaluations.

CHALLENGES AND FUTURE PROSPECTS

- Sensory acceptance: Ensuring that oleogel-based products replicate the sensory properties of traditional meat products.
- Regulatory approvals: Meeting food safety and labelling regulations for oleo gel-containing products.
- Sustainability: Leveraging sustainable sources for oleo gel production to align with global environmental goals.
- Detailed studies on protein–lipid interactions between oleogels and myofibrillar proteins and the impact of oleogels on water holding capacity, emulsion stability, and texture during storage and thermal processing.
- Lipidomic profiling of products to understand fatty acid changes post-processing and digestion.
- Exploration of underutilized plant oils and natural waxes, and focus on regulatory accepted, plant-based, and minimal additive oleogelators.

CONCLUSION

Oleo gels offer a promising innovation in the meat industry, allowing manufacturers to create healthier, high-quality meat products without compromising on sensory or functional attributes. With ongoing research and development, oleo gels could become a cornerstone in the evolution of healthier and more sustainable meat processing technologies.

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